

# Light axigluon and single top production at the *LHC*

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## Abstract

The light axigluon model can explain the Tevatron  $t\bar{t}$  forward-backward asymmetry and at the same time satisfy the constraints from the electroweak precision measurement and the *ATLAS* and *CMS* data, which induces the flavor changing ( $FC$ ) couplings of axigluon with the *SM* and new quarks. We investigate the effects of these  $FC$  couplings on the s- and t-channel single top productions at the *LHC* and the  $FC$  decays  $Z \rightarrow \bar{b}s + b\bar{s}$ ,  $t \rightarrow c\gamma$  and  $cg$ . Our numerical results show that the light axigluon can give significantly contributions to single top production and the rare top decays  $t \rightarrow c\gamma$  and  $cg$ .

**Key words:** light axigluon,  $FC$  couplings, single top production, rare top decays

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## 1. Introduction

The standard model ( $SM$ ) of particle physics has been proven to be extremely successful describing collider experimented data so far. Even the discovery of a Higgs-like particle [1, 2] has confirmed the validity of the  $SM$  at the Fermi scale. However, the  $SM$  suffers from a key theoretical drawback, the so-called "hierarchy" problem, which means that it could be a low-energy effective theory valid only up to some cut-off energy scale  $\Lambda$ , about  $TeV$  scale. So new physics beyond the  $SM$  would be in an energy range accessible at the  $LHC$  and might be discovered in coming years, although, at the moment, there is not any collider hint of new physics at the  $LHC$ .

There are various new physics models extending the gauge group of the strong interaction sector give rise to massive color-octet vector boson, for example, the topcolor models [3] and chiral color models [4]. Other examples include the extra dimensional models [5] and technicolor [6], which predict the existence of the Kaluza-Klein (KK) gluons and technirhos, respectively. Among these color-octet vector bosons, the new particles with axial-vector couplings to the  $SM$  quarks are called "axigluons", which might explain the anomalous forward-backward asymmetry ( $FBA$ ) in the  $t\bar{t}$  production observed at the Tevatron [7]. So far, there has been a significant amount of works to explain the  $t\bar{t}$   $FBA$  via axigluons, for example see [8, 9, 10, 11, 12, 13]. Furthermore, the light axigluon  $A$  with a mass  $M_A$  in the range from  $100GeV$  to  $400GeV$  can explain the  $t\bar{t}$   $FBA$  and satisfy the constraints from the  $ATLAS$  and  $CMS$  data [14, 15], as long as its decay width is large and its couplings to the  $SM$  quarks are relatively small [9, 10, 11, 12].

Top quark physics is expected to be a window to any new physics beyond the electroweak scale. At  $LHC$  energies, top quark is copiously produced both in pair and single productions, which allows for an unprecedented precision in the study of top observables, such as its couplings and rare decays [16]. At hadron colliders, single top quark production is an important process in probing the mechanism of electroweak symmetry breaking ( $EWSB$ ), providing informations complementary to those that can be obtained from top pair production [17]. Single top production is also very sensitive to new physics effects,

whose strength can be assessed by precise measurement of the production cross section.

Single top production at hadron colliders has been observed in three channels: s-channel, t-channel [18, 19] and  $tW$  associated production channel [20], which accord with the  $SM$  predictions within experimental uncertainties. *ATLAS* and *CMS* collaborations have started searching for the new physics effects on single top production.

Inspired by the solution of the light axigluon to the  $t\bar{t}$   $FBA$ , some axigluon-mediated phenomena are studied in this paper. We consider the contributions of the light axigluon with flavor changing ( $FC$ ) couplings to the  $SM$  and new quarks to the  $FC$  decays  $Z \rightarrow \bar{b}s(b\bar{s})$ , the s- and t-channel single top productions, and rare top decays  $t \rightarrow c\gamma$  and  $cg$  in the context of the light axigluon model proposed by Tavares and Schmaltz [10]. The constraints on this new physics model from the electroweak precision observables and the relevant data given by hadron colliders are taken into account in our numerical calculations.

The rest of this paper is organized as follows: After reviewing the basic ingredients of the light axigluon model, in section 2, we calculate the contributions of the light axigluon to the  $FC$  decays  $Z \rightarrow \bar{b}s$  and  $b\bar{s}$ . Corrections of the light axigluon to the cross sections of the s- and t-channel single top productions at the *LHC* are studied in section 3. The branching ratios of the rare top decays  $t \rightarrow c\gamma$  and  $cg$  induced by light axigluon exchange are given in section 4. Section 5 is devoted to simple summary.

## 2. Light axigluon and the $FC$ decays $Z \rightarrow \bar{b}s$ and $b\bar{s}$

The light axigluon model [10] is based on the gauge group  $G = SU(3)_1 \times SU(3)_2 \times SU(2) \times U(1)_Y$ , where  $SU(2) \times U(1)_Y$  is the conventional electroweak group and the extended gauge group  $SU(3)_1 \times SU(3)_2$  is spontaneously broken to the  $QCD$  gauge group  $SU(3)_C$  by the vacuum expectation value ( $VEV$ ) of a bifundamental scalar  $\phi$ . This breaking pattern yields two mass eigenstates of color-octet gauge bosons. One is massless particle, which can be identified with the  $SM$  gluon, and the other is massive particle, which is called the light axigluon  $A$ . For its couplings to the  $SM$  quarks, there are the

vector coupling  $g_V \approx 0$  and the axial-vector coupling  $g_A \neq 0$  in the case of assuming approximately parity symmetry. In order to cancel the gauge anomaly, the extra up- and down-type quarks are introduced into this model, and the lepton sector is exactly same as that of the  $SM$ . To explain the  $t\bar{t} FBA$ , the axigluon  $A$  should have mass below  $450 GeV$ , while should be broad with  $\Gamma_A/M_A \sim 10 \sim 20\%$ , where  $\Gamma_A$  and  $M_A$  represent its total decay width and mass, respectively.

In the original light axigluon model [10], the authors assume the existence of an exact global symmetry of the axigluon couplings, and thus the light axigluon only has flavor universal couplings to the  $SM$  quarks. In fact, this global symmetry is only approximate and there is mixing between new and ordinary quarks, which can induce flavor changing neutral currents ( $FCNCs$ ) at tree level [21]. The new and ordinary quarks have same  $SU(2) \times U(1)$  charge, their mixing does not give rise to the  $FC Z$  couplings at tree level. The new scalars can not induce  $FCNCs$ , thus the non-universal axigluon couplings are the main source of  $FCNC$  for this model.

In this paper we will not assume the existence of an exact global symmetry of the axigluon couplings, which allows  $FC$  couplings of the axigluons to the  $SM$  quarks. If one assumes that these  $FC$  couplings are only axial-vector couplings, which are similar with their flavor conserving couplings to the  $SM$  quarks, then the axial-vector couplings of the light axigluon to the  $SM$  quarks can be general given by the Lagrangian

$$\mathcal{L} \supset g_s [\bar{u}_i \gamma_\mu \gamma_5 (g_A^{u_i} \delta_{ij} + \varepsilon_u^{ij}) u_j A^\mu + \bar{d}_i \gamma_\mu \gamma_5 ((g_A^{d_i} \delta_{ij} + \varepsilon_d^{ij}) d_j A^\mu], \quad (1)$$

where  $A^\mu$  is the light axigluon,  $g_s$  is the  $QCD$  coupling constant,  $u_i$  and  $d_i$  are the  $SM$  up- and down-type quarks, respectively. In above equation, we have neglected the color and spinor indices.  $g_A^{u_i}$  and  $g_A^{d_i}$  are the flavor independent coupling constants and there are  $g_A^{u_i} = g_A^{d_i} = g_A^q$  [10]. The  $FC$  coupling constants  $\varepsilon_u^{ij}$  and  $\varepsilon_d^{ij}$ , which arise from flavor symmetry breaking of new and light quarks, are given by the matrices

$$\varepsilon_u = \begin{pmatrix} 0 & g^{uc} & g^{ut} \\ (g^{uc})^* & 0 & g^{ct} \\ (g^{ut})^* & (g^{ct})^* & 0 \end{pmatrix}, \quad \varepsilon_d = \begin{pmatrix} 0 & g^{ds} & g^{db} \\ (g^{ds})^* & 0 & g^{bs} \\ (g^{db})^* & (g^{bs})^* & 0 \end{pmatrix}. \quad (2)$$

The couplings of the axigluon to a pair of ordinary quarks and to the corresponding partners have opposite sign. So, in order to get suppressed couplings of the ordinary quarks to the axigluon, the extra quarks and the  $SM$  quarks should have mixing [10, 12, 22]. The mixing can be obtained by adding a Yukawa coupling involving a scalar field  $\phi$  in addition to the quark field of  $Q'$  with  $Q$ . After the spontaneous breakdown of  $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$  induced by the  $VEV$  for  $\phi$ , the new quarks from the line combinations of  $Q'$  and  $Q$  get masses, while their orthogonal combinations correspond to the  $SM$  quarks remain massless, which get masses from the  $SM$  Higgs  $VEV$  via Yukawa couplings. In the mass eigenstates, the mixing couplings of the axigluon to ordinary and new quarks, which are assumed to be axial-vector couplings, can be general written as

$$\mathcal{L}' \supset g_s g_A^{mix} [\overline{U}_{Hi} \gamma_\mu \gamma_5 (\varepsilon_{Hu}^{ij}) u_j A^\mu + \overline{D}_{Hi} \gamma_\mu \gamma_5 (\varepsilon_{Hd}^{ij}) d_j A^\mu]. \quad (3)$$

$U_{Hi}$  and  $D_{Hi}$  represent the up-type and down-type new quarks, respectively. For the mixing coupling constant  $g_A^{mix}$ , there is the relation  $(g_A^{mix})^2 + (g_A^q)^2 = 1$ . For the two matrices  $\varepsilon_{Hu}$  and  $\varepsilon_{Hd}$ , they are related through the  $SM$   $CKM$  matrix:  $\varepsilon_{Hu}^+ \varepsilon_{Hd} = V_{CKM}$ , which is similar with the case for the mixing between the T-odd and T-even quarks in the  $LHT$  model [23]. In this paper, we assume that both  $\varepsilon_{Hu}$  and  $\varepsilon_{Hd}$  are nearly equal to the identity matrix, which provides us with a set of minimal flavor mixing scenarios. We take as examples two simple cases:

Case I  $\varepsilon_{Hu} = I$ ,  $\varepsilon_{Hd} = V_{CKM}$ ,

Case II  $\varepsilon_{Hd} = I$ ,  $\varepsilon_{Hu} = V_{CKM}$ .

In case I, the mixing coupling  $g_A^{Qq}$  has no contributions to  $D^0 - \overline{D}^0$  mixing, while contributes to  $B_q^0 - \overline{B}_q^0$  and  $K^0 - \overline{K}^0$  mixings. For case II, it is obvious that the mixing coupling  $g_A^{Qq}$  can only contribute to  $D^0 - \overline{D}^0$  mixing. Reference [21] has obtained the constraints on the mixing matrix  $\varepsilon_d$  by using the available data from neutral meson mixings, such as  $B_q^0 - \overline{B}_q^0$ ,  $K^0 - \overline{K}^0$  and  $D^0 - \overline{D}^0$  mixings. Taking into account of these constants, in this section, we calculate the branching ratios of the  $FC$  decays  $Z \rightarrow \bar{b}s$  and  $b\bar{s}$  given by axigluon exchange as shown in Fig.1. The self-energy diagrams Fig.1(b) and (c) contribute a finite field renormalization and the individual diagrams are finite

[24]. To fulfill the broad width of the axigluon, the first and second generation new quarks should be degenerate and lighter than the axigluon, while the third generation new quarks must be heavier [10]. So we think that the contributions of the third generation new quarks to the  $FC$  decays  $Z \rightarrow \bar{b}s(b\bar{s})$  decouple and only consider the contributions of the first and second generation new quarks. In our numerical estimation, we will take  $M_{D_{H1}} = M_{D_{H2}} = M_H = 0.2M_A$ . In this case, one can safely neglect the phase space suppression effect for the axigluon decaying to one new quark and one ordinary quark and there should be  $\Gamma_A/M_A \sim 10 \sim 20\%$ .

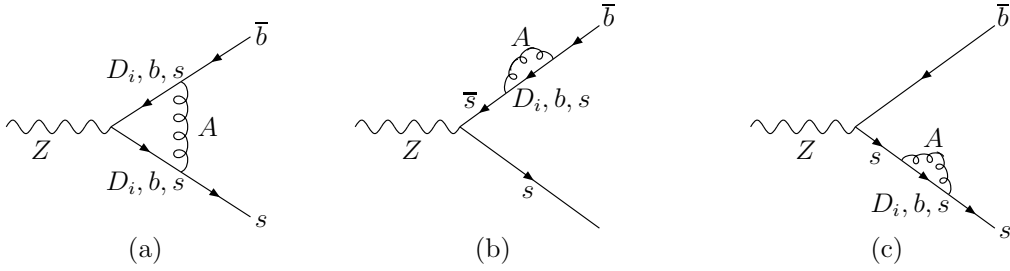


Figure 1: One-loop Feynman diagrams for the  $FC$  decay  $Z \rightarrow \bar{b}s$  induced by light axigluon exchange.

The light axigluon model predicts the existence of new scalar, which also has the mixing couplings to new and ordinary quarks. However, it can not induce  $FC$  couplings at tree level and thus in this paper we neglect the effects of the new scalar on the  $FC$  processes  $Z \rightarrow \bar{b}s$  and  $b\bar{s}$ .

The corrections of color-octet gauge boson to the  $Zb\bar{b}$  coupling are firstly studied by Ref.[25] in the context of topcolor models, which contain only the leading-logarithmic contributions. The full one-loop results for the corrections of the axigluon to the  $Zb\bar{b}$  coupling are given in Refs.[11, 12] in the case of neglecting the bottom quark mass. Ref.[12] have further computed the contributions from new quarks and new scalar to the  $Zb\bar{b}$  coupling and find that the two kinds of contributions have opposite sign and the effect of new scalar is much smaller than that of new quarks. Following Refs.[11, 12], we can straightforwardly calculate the contributions of the light axigluon model to the  $FC$

couplings  $Z\bar{b}s$  and  $Zb\bar{s}$ . Then, the effective  $Z\bar{b}s$  coupling can be written as

$$g_P^{Zbs} = \frac{\alpha_s}{3\pi} g_P^{Zbb} [2g_P^{Abb} g_P^{Abs} \kappa(x_z) + (g_A^{mix})^2 \kappa(x_z, x_h) (\varepsilon_{Hd}^{*13} \varepsilon_{Hd}^{12} + \varepsilon_{Hd}^{*23} \varepsilon_{Hd}^{22})], \quad (4)$$

where  $P = L$  and  $R$ .  $g_P^{Zbb}$  and  $g_P^{Abb}$  represent the couplings of the gauge boson  $Z$  and axigluon  $A$  to the bottom quark pairs, respectively. The explicit expressions of the factors  $\kappa(x_z)$  and  $\kappa(x_z, x_h)$  have been given in Ref.[12]. Since the couplings of the axigluon to pair of ordinary quarks and pair of new quarks are flavor universal and the new and ordinary quarks have same  $SU(2) \times U(1)$  charge, in above equation we have added the contributions of the ordinary quarks  $b$  and  $s$ , and taken

$$g_L^{Zbb} = g_L^{ZD_iD_i} = \frac{e}{4S_W C_W} (1 - \frac{2}{3} S_W^2), \quad g_R^{Zbb} = g_R^{ZD_iD_i} = -\frac{e}{4S_W C_W} \cdot \frac{2}{3} S_W^2, \quad (5)$$

where  $i = 1$  and  $2$ ,  $S_W = \sin \theta_W$  and  $C_W = \cos \theta_W$ ,  $\theta_W$  is the Weinberg angle. The  $FC$  coupling  $g_P^{Abs}$  can contribute to  $B_s^0 - \bar{B}_s^0$  mixing at tree level and its upper bound has been obtained by Ref.[21] as  $|g_L^{bs}| = |g_R^{bs}| = |g_A^{bs}| \leq 1.83 \times 10^{-3}$ . In fact, for the case I, the new quarks can also generate contributions to  $B_s^0 - \bar{B}_s^0$  mixing via box diagrams that contain the light axigluon and new quark. However, the contributions from box diagrams are suppressed with respect to axigluon tree-level contributions by a loop factor  $1/(16\pi^2)$  and two additional mixing matrix elements  $\varepsilon_{Hd}^{i3}$  and  $\varepsilon_{Hd}^{i2}$ . Therefore they cannot compete with the latter and are negligible. As numerical estimation, we will take  $g_A^{bs} = 1.83 \times 10^{-3}$ ,  $g_L^{Abb} = -g_R^{Abb} = g_A^q$ .

In the  $SM$ , the  $FC$  decay  $Z \rightarrow \bar{b}s + b\bar{s}$  originates from one loop diagrams with branching ratio  $\sim 3 \times 10^{-8}$  [26]. For future linear collider ( $ILC$ ), the expected sensitivity to the branching ratios of rare  $Z$  decays can be improved from  $10^{-5}$  at the  $LEP$  to  $10^{-8}$  at the Giga  $Z$  [27]. The new physics effects might be detectable via  $Z \rightarrow bs$  if it indeed affects this decay. A lot of theoretical studies involving the  $FC$  decay  $Z \rightarrow bs$  have been given within some popular models beyond the  $SM$ , where its branching ratio can be significantly enhanced [28].

Using the effective couplings  $g_L^{Zbs}$  and  $g_R^{Zbs}$  given by Eq.(4), we can easily calculate the partial width  $\Gamma(Z \rightarrow \bar{b}s + b\bar{s})$ . The numerical results for the branching ratio  $Br(Z \rightarrow$

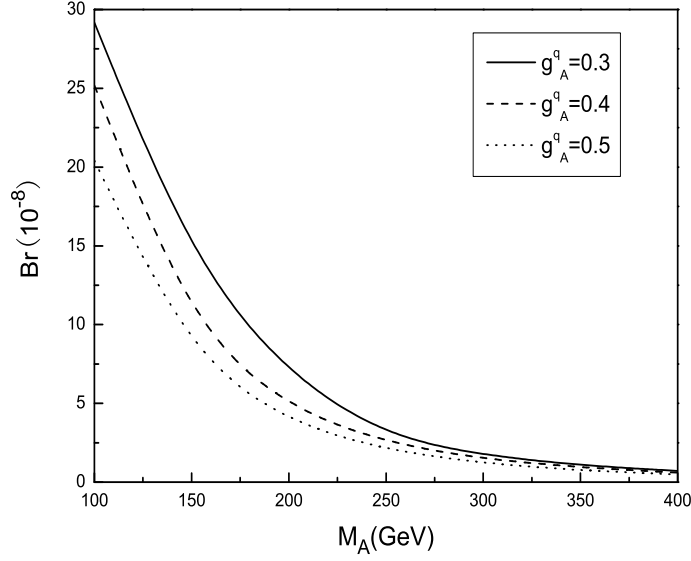


Figure 2: Variation of the branching ratio  $Br(Z \rightarrow \bar{b}s + b\bar{s})$  with the axigluon mass  $M_A$  for  $g_A^{bs} = 1.83 \times 10^{-3}$ ,  $\varepsilon_{Hd} = V_{CKM}$  and three values of the coupling parameter  $g_A^q$ .

$\bar{b}s + b\bar{s}) = \Gamma(Z \rightarrow \bar{b}s + b\bar{s})/\Gamma_{total}$  are shown in Fig.2, in which we have taken the  $SM$  input parameters as:  $\alpha_s(m_Z) = 0.118$ ,  $S_W^2 = 0.231$ ,  $\Gamma_{total} = 2.4945 GeV$ , and  $M_Z = 91.1875 GeV$  [29]. If the light axigluon can explain the  $t\bar{t}$   $FBA$  and at the same time satisfy the constraints from the electroweak precision observables and the relevant data given by hadron colliders, its mass should be in the range of  $100 GeV \sim 400 GeV$ , its total decay width  $\Gamma_t^A = (0.1 \sim 0.2)M_A$  and the flavor conserving coupling  $g_A^q$  might be in the range of  $0.3 \sim 0.5$  [9, 10, 11, 12]. In our numerical estimation we have considered the effects of the axigluon width and taken  $\Gamma_t^A = 0.1M_A$ . For the mixing between the  $SM$  and new quarks, we have taken case I and assumed  $M_H = 0.2M_A$ . One can see from Fig.2 that, in most of the parameter space, the value of the branching ratio  $Br(Z \rightarrow \bar{b}s + b\bar{s})$  is smaller than  $1 \times 10^{-8}$ , which is still below the  $SM$  prediction. So considering the constraints of  $B_s^0 - \bar{B}_s^0$  mixing on the  $FC$  coupling  $g_A^{bs}$ , the contribution of the light axigluon to the



rare decays  $Z \rightarrow \bar{b}s$  and  $b\bar{s}$  is very difficult to be detected in near future. Certainly, if we assume  $\varepsilon_{Hd} \neq V_{CKM}$ , the numerical results should has some changes.

### 3. The $FC$ couplings of the light axigluon $A$ and single top production at the $LHC$

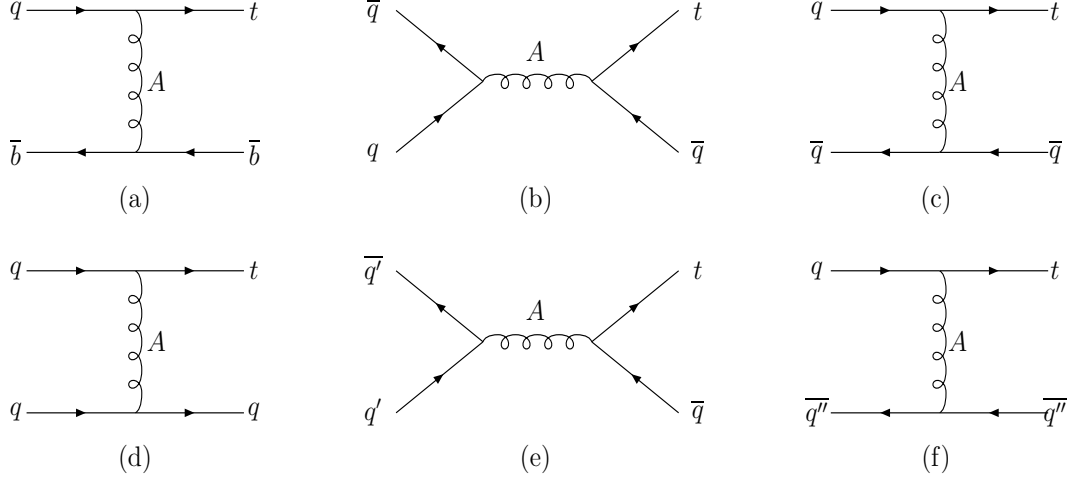


Figure 3: Leading order Feynman diagrams for  $t\bar{b}$  and  $t\bar{j}$  production contributed by the  $FC$  couplings  $g_A^{tq}$ , in which  $q = u, c$ ,  $q' = d, s, b$ , and  $q'' = d, s$ .

In the  $SM$ , single top production dominantly occurs through electroweak processes, which are customary divided into three production channels: t-channel exchange of a space-like W boson, s-channel production and decay of a time-like W boson, and associated production of a top quark and an on-shell W boson. These partonic processes have their own distinct kinematics and do not interfere with each other. Both at Tevatron and the  $LHC$ , the t-channel process is dominant one, which in five flavor ( $5F$ ) scheme proceeds via the partonic processes  $qb \rightarrow q't$  and  $\bar{q}b \rightarrow \bar{q}'t$  for single top production, and  $q\bar{b} \rightarrow q'\bar{t}$  and  $\bar{q}\bar{b} \rightarrow \bar{q}'\bar{t}$  for single antitop production. The s-channel partonic processes are  $q\bar{q}' \rightarrow t\bar{b}$  and  $\bar{q}q' \rightarrow \bar{t}b$  for single top and antitop productions, respectively. The contributions of charged and neutral color-octet vector bosons to top pairs and single top production has been studied in Refs.[13, 30]. In this section we will consider the corrections of the light axigluon to the s- and t-channel single top productions via the  $FC$  couplings  $g_A^{tq}$  with

$q = u$  or  $c$ . The relevant Feynman diagrams are shown in Fig.3.

For the partonic process  $q\bar{b} \rightarrow t\bar{b}$  as shown in Fig.3 (a), the differential cross section with respect to emerging angle of the single top quark  $\cos\theta_t$  can be written as

$$\frac{d\sigma(t\bar{b})}{d\cos\theta_t} = \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^b)^2}{9\hat{s}} P_t[\hat{s}(\hat{s} - m_t^2) + \hat{t}(\hat{t} - m_t^2)]. \quad (6)$$

The partonic process  $q\bar{q} \rightarrow t\bar{q}$  is composed of the s- and t-channel diagrams corresponding to Fig.3 (b) and 3 (c). Its differential cross section is given by

$$\begin{aligned} \frac{d\sigma(t\bar{q})}{d\cos\theta_t} = & \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^q)^2}{9\hat{s}} \{P_s[\hat{u}(\hat{u} - m_t^2) + \hat{t}(\hat{t} - m_t^2)] \\ & - \frac{P_s P_t}{3}(\hat{s} - M_A^2)(\hat{t} - M_A^2)\hat{u}(\hat{u} - m_t^2) \\ & + P_t[\hat{s}(\hat{s} - m_t^2) + \hat{u}(\hat{u} - m_t^2)]\}. \end{aligned} \quad (7)$$

The differential cross section of the t+u channel partonic process  $qq \rightarrow t+q$  can be written as

$$\begin{aligned} \frac{d\sigma(tq)}{d\cos\theta_t} = & \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^q)^2}{9\hat{s}} \{P_t[\hat{u}(\hat{u} - m_t^2) + \hat{s}(\hat{s} - m_t^2)] \\ & + P_t P_u(\hat{t} - M_A^2)(\hat{u} - M_A^2)\hat{s}(\hat{s} - m_t^2) \\ & + P_u[\hat{t}(\hat{t} - m_t^2) + \hat{s}(\hat{s} - m_t^2)]\}. \end{aligned} \quad (8)$$

The differential cross section for the s-channel partonic  $\bar{q}'q' \rightarrow t\bar{q}$  as shown in Fig.3 (e) is given by

$$\frac{d\sigma_s(t\bar{q})}{d\cos\theta_t} = \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^{q'})^2}{9\hat{s}} P_s[\hat{u}(\hat{u} - m_t^2) + \hat{t}(\hat{t} - m_t^2)]. \quad (9)$$

The explicit expression of the differential cross section for the t-channel  $q\bar{q}'' \rightarrow t\bar{q}''$  is same as that for the process  $q\bar{b} \rightarrow t\bar{b}$ , as long as replace the initial state  $b$  quark by the quark  $q''$  ( $d$  or  $s$ ). In above equations,  $\beta = 1 - \frac{m_t^2}{\hat{s}}$ ,  $\hat{s}$ ,  $\hat{t}$ , and  $\hat{u}$  are the usual Mandelstam variables,

$$P_i = \frac{1}{(i - M_A^2)^2 + M_A^2\Gamma_A^2} \quad \text{with } i = \hat{s}, \hat{t}, \text{ or } \hat{u}. \quad (10)$$

Using above equations we can calculate the cross sections of  $t\bar{b}$  and  $tj$  production at the  $LHC$  induced by the light axigluon with the  $FC$  coupling  $g_A^{tq}$ . In our numerical

calculations, we use the leading order parton distribution function of CTEQ6L1 [31] and choose the factorization and renormalization scales to be  $\mu_f = \mu_r = m_t/2$  with  $m_t = 173\text{GeV}$ . Our numerical results are added  $t\bar{b}$  and  $\bar{t}b$  for the process  $pp \rightarrow tb$ , and similar for  $tj$  production with  $j = u, c, d$ , and  $s$ . It is obvious that the production cross sections depend on the mass parameter  $M_A$ , the coupling parameters  $g_A^{tq}$  and  $g_A^q$ , where we have taken  $g_A^{tu} = g_A^{tc}$  and the flavor conserving coupling  $g_A^q$  being flavor universal.

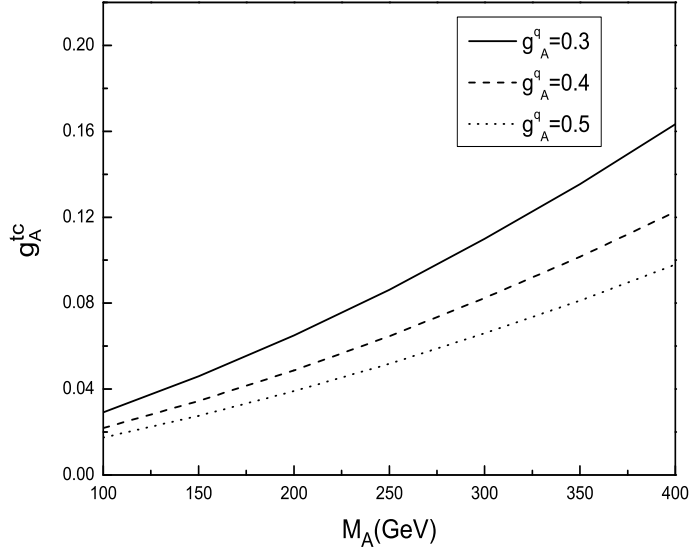


Figure 4: In the case of  $\delta\sigma^s/\sigma_{SM}^s = 10\%$ , the  $FC$  coupling  $g_A^{tq}$  as function of the axigluon mass  $M_A$  for  $g_A^q = 0.3$ (solid line),  $0.4$ (dashed line) and  $0.5$ (dotted line).

In the  $SM$ , single top production at hadron colliders was first considered in Ref.[32]. Now the production cross sections for the s- and t-channels have been calculated up to next-to-next-to leading logarithm ( $NNLL$ ) accuracy [33]:  $\sigma_s = 1.04 \pm 4\% \text{ pb}$  and  $\sigma_t = 2.26 \pm 5\% \text{ pb}$  at Tevatron with the centre-of-mass ( $c.m.$ ) energy  $\sqrt{s} = 1.96\text{TeV}$  and  $\sigma_s = 12 \pm 6\% \text{ pb}$  and  $\sigma_t = 243 \pm 4\% \text{ pb}$  at the  $LHC$  with  $\sqrt{s} = 14\text{TeV}$ . The s- and t-channel cross sections have been measured at Tevatron by  $CDF$  and  $DO$  collaborations and the measurement precision can reach 18% [18]. The measurement precision for the

t-channel cross section at the  $8TeV$  *LHC* reported by *ATLAS* and *CMS* is about 15% [19]. It will be enhanced in coming years. For example, Ref.[34] has shown that the cross section of the t-channel single top production at the  $14TeV$  *LHC* can be measured with a precision of 5%.

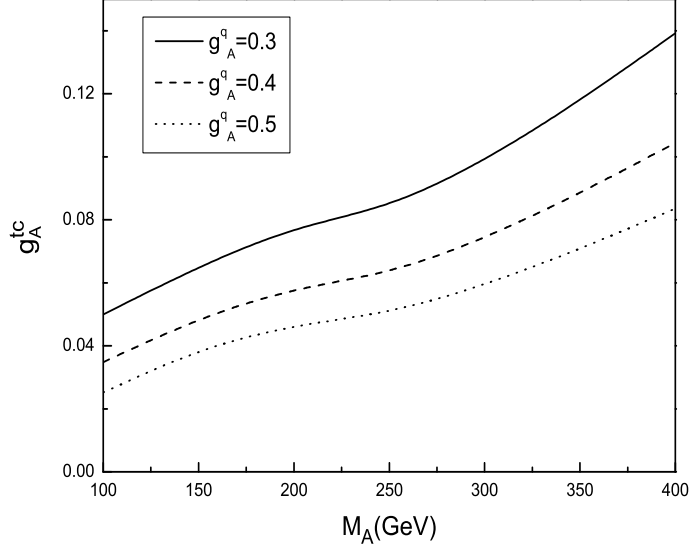


Figure 5: In the case of  $\delta\sigma^t/\sigma_{SM}^t = 10\%$ , the *FC* coupling  $g_A^{tq}$  as function of the axigluon mass  $M_A$  for  $g_A^q = 0.3$ (solid line),  $0.4$ (dashed line) and  $0.5$ (dotted line).

From above discussions we can see that the theoretical error of the *SM NNLO* cross section at the  $14TeV$  *LHC* for the s- and t-channel productions could be as large as 5%, the same amount of the expected precision at the  $14TeV$  *LHC*. So if the relative correction of the light axigluon to the single top production cross section is larger than 10%, the  $14TeV$  *LHC* should detect this correction effect. In Fig.4 and Fig.5 we demand that  $\delta\sigma^s/\sigma_{SM}^s = 10\%$  and  $\delta\sigma^t/\sigma_{SM}^t = 10\%$ , where  $\sigma_{SM}^s$  and  $\sigma_{SM}^t$  are the *SM NNLO* predictions for the s- and t-channel single top production cross sections at the *LHC* with  $\sqrt{s} = 14TeV$ ,  $\delta\sigma^s$  and  $\delta\sigma^t$  are induced by the light axigluon *A*, and plot the *FC* coupling  $g_A^{tq}$  as a function of the mass parameter  $M_A$  for different values of the flavor

conserving  $g_A^q$ . In our numerical calculation, we have taken the central values for  $\sigma_{SM}^s$  and  $\sigma_{SM}^t$ . From these figures one can see that the contributions of the light axigluon to the production cross sections of the processes  $pp \rightarrow tb + X$  and  $pp \rightarrow tj + X$  increase as the coupling parameters  $g_A^{tq}$  and  $g_A^q$  increasing, while decrease as  $M_A$  increasing. For  $100\text{GeV} \leq M_A \leq 400\text{GeV}$  and  $0.3 \leq g_A^q \leq 0.5$ , the values of  $FC$  coupling  $g_A^{tq}$  are in the ranges of  $0.017 \sim 0.163$  and  $0.024 \sim 0.139$  for  $\delta\sigma^s/\sigma_{SM}^s = 10\%$  and  $\delta\sigma^t/\sigma_{SM}^t = 10\%$ , respectively. We expect that, in near future, the *LHC* can authenticate this correction effect on single top production or at least give constraint on the  $FC$  coupling  $g_A^{tq}$ .

#### 4. The light axigluon and the rare top decays $t \rightarrow c\gamma$ and $cg$

It is well known that in the *SM* the rare top decays  $t \rightarrow qV$  ( $q = u, c$  and  $V = \gamma, g, Z$ ) mediated by *FCNCs* are highly *GIM* suppressed with branching ratios of  $Br(t \rightarrow cV) \sim 10^{-14} \sim 10^{-12}$  [35], which are far below the detectable level of current or near future experiments. However, some new physics models can enhance these branching ratios significantly [36]. So rare top decays offer an opportunity to test the *SM* and search for new physics effects. Any positive signal of rare top decay processes would clearly indicate new physics beyond the *SM*.

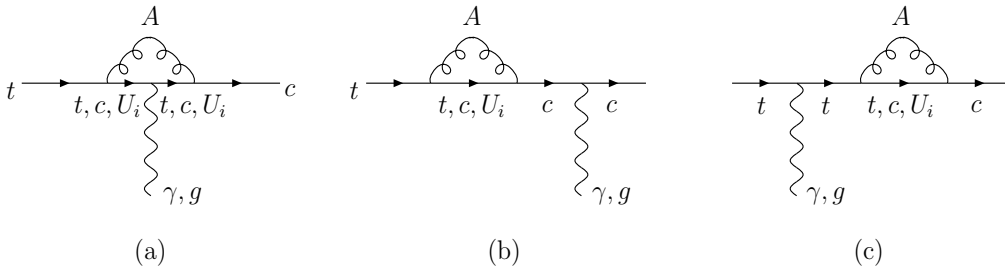


Figure 6: Feynman diagrams for the rare top decays  $t \rightarrow c\gamma$  and  $cg$  coming from the  $FC$  coupling  $g_A^{tc}$ , in which  $i = 1$  and  $2$ .

On the experimental side, rare top decays are being searched for at Tevatron [37] and *LHC* [38, 39]. *ATLAS* collaboration has set upper limit on the branching ratio  $Br(t \rightarrow cg) < 2.7 \times 10^{-4}$  at 95% C.L. [39]. The sensitivity of *ATLAS* to the branching

ratio  $Br(t \rightarrow c\gamma)$  is expected to be of the order of  $10^{-4}$  [40].

From discussions given in above sections we can see that the light axigluon with  $FC$  couplings can contribute rare top decays. In this section we will calculate the branching ratios  $Br(t \rightarrow c\gamma)$  and  $Br(t \rightarrow cg)$  induced by the light axigluon. The relevant Feynman diagrams are shown in Fig.6. In this section, we also assume that the contributions of the third generation new quarks to the rare top decays  $t \rightarrow c\gamma$  and  $t \rightarrow cg$  decouple. Compared to the  $FC$  couplings of the light axigluon  $A$  to the new quarks and the  $SM$  quarks, the  $FC$  couplings of the scalar  $\phi$  to the new quarks and the  $SM$  quarks arise at higher order, their  $FC$  effects are much smaller than those induced by the axigluon  $A$ . Thus, in this section, we neglect the contributions of the scalar  $\phi$  to the rare top decays  $t \rightarrow c\gamma$  and  $t \rightarrow cg$  as done for  $Z \rightarrow bs$  in section 2.

Considering electromagnetic gauge invariance, the amplitude of the rare decay  $t \rightarrow c\gamma$  can be general written as

$$M(t \rightarrow c\gamma) = i\bar{u}(P_c)\sigma^{\mu\nu}q_\nu(A_\gamma + B_\gamma\gamma_5)u(P_t)\varepsilon_\mu^*(q), \quad (11)$$

where  $q = P_t - P_c$  is the photon momentum and  $\varepsilon$  is its polarization vector, in which  $P_t$  and  $P_c$  represent the momenta of top and charm quarks, respectively. A similar structure is valid for  $t \rightarrow cg$  with form factors  $A_g$  and  $B_g$ . For the light axigluon  $A$  with zero vector couplings to the  $SM$  and new quarks i.e.  $g_V^{tq} \approx 0$ ,  $g_V^{Q_Hq} \approx 0$  and  $g_V^q \approx 0$  [10, 12], there are  $A_\gamma \neq 0$ ,  $A_g \neq 0$  and  $B_\gamma = 0$ ,  $B_g = 0$ . Recently, Ref.[41] has calculated the contributions of color-singlet gauge bosons predicted by the 331 models to the rare top decay  $t \rightarrow c\gamma$  and give the explicit expressions for the relevant form factors. In this paper we will use LoopTools [42] to obtain our numerical results.

Using Eq.(11), the partial widths of  $t \rightarrow c\gamma$  and  $t \rightarrow cg$  contributed by the light axigluon can be written as

$$\Gamma(t \rightarrow c\gamma) = \frac{m_t^3}{8\pi}(1 - \frac{m_c^2}{m_t^2})^3|A_\gamma|^2, \quad (12)$$

$$\Gamma(t \rightarrow cg) = \frac{C_F m_t^3}{8\pi}(1 - \frac{m_c^2}{m_t^2})^3|A_g|^2, \quad (13)$$

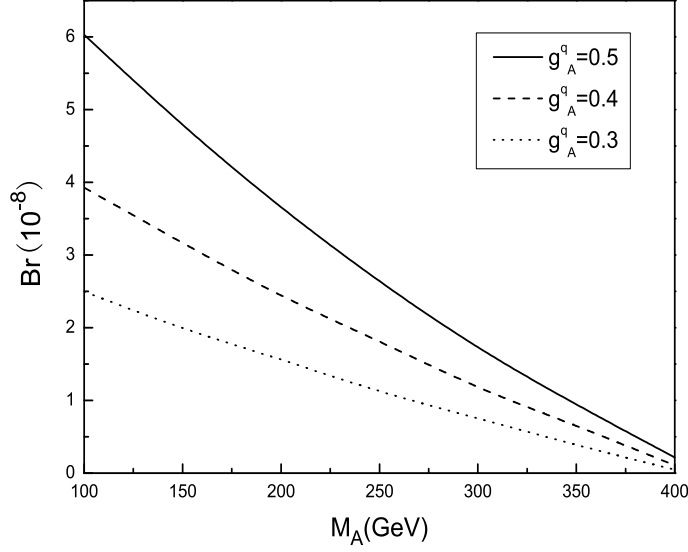


Figure 7: The branching ratio  $Br(t \rightarrow c\gamma)$  as a function of the axigluon mass  $M_A$  for three values of the flavor conserving coupling  $g_A^q$ .

where  $C_F = 4/3$  is a color factor.

To obtain numerical results, we have assumed that the top total decay width is dominated by the decay  $t \rightarrow Wb$ . The  $FC$  coupling  $g_A^{tc}$  is determined by the parameters  $g_A^q$  and  $M_A$  via the relation  $\delta\sigma^t/\sigma_{SM}^t = 10\%$ . For calculation the contributions of the first and second generation new quarks, we take the case II:  $\varepsilon_{Hd} = I$ ,  $\varepsilon_{Hu} = V_{CKM}$  and assume  $M_H = 0.2M_A$ . In Fig.7 and Fig.8 we plot the branching ratios  $Br(t \rightarrow c\gamma)$  and  $Br(t \rightarrow cg)$  as functions of the axigluon mass  $M_A$  for three values of the flavor conserving coupling  $g_A^q$ . One can see from these figures that the light axigluon  $A$  can indeed enhance the branching ratios  $Br(t \rightarrow c\gamma)$  and  $Br(t \rightarrow cg)$ . For  $0.3 \leq g_A^q \leq 0.5$  and  $100\text{GeV} \leq M_A \leq 400\text{GeV}$ , the values of  $Br(t \rightarrow c\gamma)$  and  $Br(t \rightarrow cg)$  are in the ranges of  $4.8 \times 10^{-9} \sim 5.9 \times 10^{-8}$  and  $1.1 \times 10^{-8} \sim 1.3 \times 10^{-6}$ , respectively. Replacing the  $FC$  couplings  $g_A^{tc}$  and  $g_A^{Uic}$  by  $g_A^{tu}$  and  $g_A^{Uiu}$ , we can easily calculate the contributions of the light axigluon  $A$  to the rare top decays  $t \rightarrow u\gamma$  and  $ug$ .

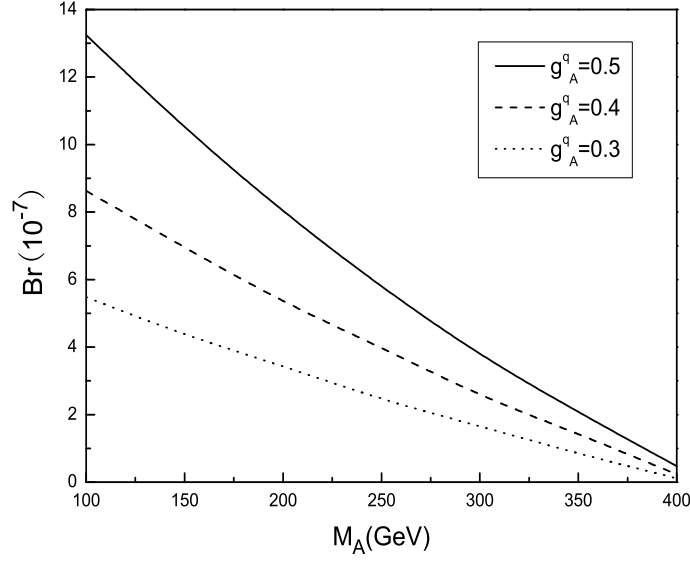


Figure 8: The branching ratio  $Br(t \rightarrow cg)$  as a function of the axigluon mass  $M_A$  for three values of the flavor conserving coupling  $g_A^q$ .

## 5. Conclusions

The light axigluon  $A$  with a mass  $M_A$  in the range from  $100\text{GeV}$  to  $400\text{GeV}$  predicted by the light axigluon model [10] can explain the  $t\bar{t}$   $FBA$  and satisfy the constraints from the *ATLAS* and *CMS* data, as long as its decay width is large and its couplings to the  $SM$  quarks are relatively small. In order to get suppressed couplings of the light axigluon  $A$  to the  $SM$  quarks, the new quarks and the  $SM$  quarks should have mixing, which can induce the  $FC$  couplings to the new quarks and the  $SM$  quarks. Furthermore, to fulfill the broad width of the axigluon, the new quarks, at least the first and second generation new quarks, are lighter than the light axigluon. In this paper, we assume the flavor conserving axigluon couplings are universal and pure axial vector-like, and investigate some  $FC$  phenomena mediated by the light axigluon.

The contributions of the light axigluon model to the  $FC$  decays  $Z \rightarrow \bar{b}s, b\bar{s}$  and  $t \rightarrow c\gamma, cg$  mainly come from the  $FC$  quark- quark- axigluon coupling  $g_A^{qq'}$  and the  $FC$



quark- new quark- axigluon coupling  $g_A^{qQ_H}$ . Considering the constraints of meson mixing on the  $FC$  coupling  $g_A^{qq'}$  and assuming that both  $\varepsilon_{Hu}$  and  $\varepsilon_{Hd}$  are nearly equal to the identity matrices and satisfy the relation  $\varepsilon_{Hu}^\dagger \varepsilon_{Hd} = V_{CKM}$  to give the value of  $g_A^{qQ_H}$ , we calculate the branching ratios  $Br(Z \rightarrow \bar{b}s + b\bar{s})$ ,  $Br(t \rightarrow c\gamma)$  and  $Br(t \rightarrow cg)$  in the context of the light axigluon model. Our numerical results show that, in most of parameter space, the value of the branching ratio  $Br(Z \rightarrow \bar{b}s + b\bar{s})$  is smaller than  $1 \times 10^{-8}$ , which is still below the  $SM$  prediction. Compared to the  $SM$  predictions, the branching ratios  $Br(t \rightarrow c\gamma)$  and  $Br(t \rightarrow cg)$  can be significantly enhanced in the light axigluon model, while are still lower than the corresponding current experimental upper limits.

It is well known that single top production is very sensitive to new physics beyond the  $SM$ , whose effects can be assessed by precise measurement of the production cross section. In this paper, we study the correction effects of the light axigluon  $A$  to the s- and t-channel single top productions at the  $LHC$ . We find that, in near future, the  $LHC$  should observe this correction effect with reasonable values for the  $FC$  coupling  $g_A^{tq}$  or at least give constraint on the  $FC$  coupling  $g_A^{tq}$ . If one demands  $\delta\sigma^s/\sigma_{SM}^s = 10\%$  and  $\delta\sigma^t/\sigma_{SM}^t = 10\%$ , the values of the  $FC$  coupling  $g_A^{tq}$  should be in the ranges of  $0.017 \sim 0.163$  and  $0.024 \sim 0.139$ , respectively.

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